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LIQUEFIED METAL JET PROGRAM AUTOMATION AND ROBOTICS RESEARCH INSTITUTE (ARRI)

R&D QUARTERLY STATUS REPORT PROGRAM FINANCIAL STATUS

REPORTING PERIOD: 15 APRIL 1994 THROUGH 15 JULY 1994

Sponsored by:

Advanced Research Projects Agency (ARPA)
Contracts Management Office (CMO)
Liquefied Metal Jet Program (LMJP)

ARPA Order No. 9328/03

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"The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed implied, of the Advanced Research Projects Agency or the U.S. Government."

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Texas Instruments Incorporated
Defense Systems & Electronics Group
13500 North Central Expressway
Dallas, Texas 75243

12 July 1994
2309

TEXAS INSTRUMENTS

LIQUIFIED METAL JET PROGRAM
AUTOMATION AND ROBOTICS RESEARCH INSTITUTE (ARRI)

R&D QUARTERLY STATUS REPORT
DATA ITEM 0002AA
15 APRIL 1994 THROUGH 15 JULY 1994

1.0 INTRODUCTION

During this reporting period, we completed the design and assembly of the no-lead system, continued to pursue several risk reduction activities, and initiated design efforts for the copper system. Formal testing of the no-lead system began on July 1, 1994.

2.0 PROGRESS DURING THE REPORTING PERIOD

- Completed design and assembly of no-lead system.
- Completed critical design review for no-lead system with TI.
- Continued to investigating several types of filtration material.
- Completed design and assembly of manual drop solder system except for environmental enclosure.
- Redesigned and fabricated new manual drop head to resolve problems with leaks and pressure.
- Completed Test Plan.
- Initiated formal testing of the no-lead system.
- Initiated the preliminary design of the copper system.
- Continued to evaluate selected materials for the copper system fluidizer pot and tubing.
- Continue work with POCO Graphite in Decatur, TX to develop a containment system for liquid copper.

3.0 PLANNED ACTIVITIES FOR NEXT REPORTING PERIOD

- Formal testing of no lead system.
- First test coupons - Third quarter.
- Risk reduction testing of construction materials for copper system.
- Formal testing of manual drop solder system.
- Design and assembly environmental enclosure for manual drop solder system.

4.0 EQUIPMENT PURCHASED OR CONSTRUCTED

Assembled/Constructed:

- No-lead system and control system
- Revised manual drop system for solder

Purchased

- Oxygen trace analyzer
- Control computer
- Lab view controllers
- Water vapor monitor
- High speed, high current, pulser amplifier
- Custom light ring.

5.0 NOTIFICATION OF KEY PERSONNEL CHANGES

None

6.0 INFORMATION FROM TRIPS, MEETINGS, AND SPECIAL CONFERENCES

- Held critical design review on May 6, 1994.
- Met with Automated Products (Steve Dillier).
- Finalized non-disclosure agreement with Sandia National Laboratory (Fred Yost).
- Presented status of modeling efforts to Sandia National Laboratory, June 1, 1994.
- Met with NCMS (Electronics Special Interest Group) concerning jetting applications.
- Held an MCM conference to help establish process requirements.

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LIQUEFIED METAL JET PROGRAM AUTOMATION AND ROBOTICS RESEARCH INSTITUTE (ARRI)

QUARTERLY TECHNICAL REPORT

REPORTING PERIOD: 15 APRIL 1994 THROUGH 15 JULY 1994

Sponsored by:

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12 July 1994
2309

TABLE OF CONTENTS

LIQUEFIED METAL JET
QUARTERLY TECHNICAL REPORT
15 APRIL 1994 THROUGH 15 JULY 1994

1.0 INTRODUCTION

This report covers the period from April 15, 1994 to July 15, 1994. The Quarterly Technical Reports are organized by the statement of work (SOW) listed in section 5.0 of the proposal. These are:

- Reports and demonstration
- Equipment
- System test and experimentation
- Test coupon evaluation
- Technology transfer.

2.0 REPORTS AND DEMONSTRATION, SOW 5.1

A Test Plan has been developed and is included as Appendix A.

3.0 EQUIPMENT, SOW 5.2

A critical design review was held on May 6, 1994 for the no-lead system. The attendees were:

Name	Title	Company
Mike R. Diver	Staff Engineer, ARRI	UTA-ARRI
Nicholas J. Dringenberg	Staff Engineer, ARRI	UTA-ARRI
Patrick N. DuBois	PAAG Group Coordinator	UTA-ARRI
Billy Fornero	Manager, Microelectronics Engr.	TI
John F. Hendrickson	Research Assistant, ME	UTA
Brendon R. Holt	Graduate Research Assistant	UTA
Dave Mendez	Manager Austin PWB Design Engr.	TI
John W. Priest	Professor, IMSE	UTA
Jim Reed	Engineer, Austin PWB	TI
Charles Smith, Jr.	Professor, Electrical Engineering	UTA
Norman J. Spayd	Sci. Inst. Maker	UTA-ARRI
Rob Terrill	Engineer, Microelectronics	TI
Kurt Wachtler	Semiconductor Packaging	TI
Elwin Whetsel	Manager LMJ Program	TI

Several areas were identified for further study. Items to evaluate include: (TBD)

1. Reduce size of coupons to 12" × 12" (min. 6" × 6") for a 18" × 12" fixture (complete)

2. Revise x/y placement budget - especially Cμ (00.002) (complete)

    - Prototype and production

3. Incorporate DOE into Test Plan (complete)

4. Evaluate backing for test substrates in via fill up; incorporate into Test Plan (complete)

5. Austin to provide baseline data coupon, copper substrate, solder ball test

6. Test coupon vias procedure; 0.0003 mil deep, 0.0006 mil * 60 mil, 5 * 3 (complete)

7. Install high temperature Interlock to TI specification

8. Contacts

    - Sheldall, ARPA contract for flex circuits
    - Gould, copper foil, cleaning oxides
    - Ferros, ceramic filters (complete)
    - Climax, copper, cleaning oxides

9. TI Austin to provide copper substrate materials, requirements matrix, metric measures

10. Set up meeting on dialectics/polymers

    - Ideas/applications for polymer project
    - Upcoming NCMS project?

11. Contract and set up meeting with Attleboro/MIT/MPM in late July for material issues

    - Constructions material, filtering, environment, lower cost, high temperature conductors
    - Should complete details on testing and design

12. Set up Austin visit for test metrics and coupons (in process)

13. Add tests to test plan (complete)

    - Add adhesion

- Pull off test
- Porosity measure
- Elongation of Cμ

14. New Cμ application, add to Test Plan (complete)
    - Fill up vias
15. Market/w/o process
    - TI cost
    - Formal process plan/market
    - Die balls application, also evaluate barrier metals
    - Identify Killer product characteristics (contact GM & TI)
    - Visit GM-Delco (Kokomo)
    - Evaluate economics; focus on Delco, high temp, flip chip, flex circuit for automotive applications
    - Frequency propagation 200 MHz, 10GHz
    - Wait on results of filter tests
    - Call Delco for Copper/PWB requirements
16. Attend metal finish symposium (in process)
    - Identify other LMJ application
    - Identify other filters
17. Filtering using weight for separating contaminants - centrifuge or bubble Nitrogen

3.1 Fluidizer, SOW 5.2.1

The fluidizer module for the LMJ system converts the solid metal feedstock to liquid. This includes engineering design, fabrication, thermal management integration and functional testing of the fluidizer module to introduce the metal feedstock at a predetermined rate into a high temperature metal chamber. Propelling forces are required to drive the LMJ at the predetermined velocity. The resulting liquefied metal will be transitioned to the droplet generator for subsequent droplet formation.

Test results of the no lead fluidizer continue to show minor problems including:

1. Leaks
2. Pressure controller
3. Electromagnetic interference
4. Difficulty loading raw material
5. Difficulty cleaning and removing dross
6. Materials procurement.

Conceptual design of the fluidizer for the copper system is continuing. Due to the much higher temperature needed to melt copper (2,000°F), a complete redesign is required. Major areas of evluation continue to include:

- Melting method; induction, conduction, radiation, etc.
- Fluidizer construction material, ceramic, tungsten, molybdenum, graphite, boron nitride
- Sealing bolts, flanges, etc.
- Determining the volme of metal needed to be melted
- Optical observation and measurement

Several options are still under study.

Several risk reduction efforts have been initiated. One of the major efforts is the manual drop system as reported in the last quarterly report. The manual drop system has been focusing on methods for melting copper and a drop on demand head. A furnace for melting copper has been procured and is being tested. Demand prototypes for the manual drop system continue to fabricated and tested. None of these prototypes are acceptable but progress is being make. The goal is have a working manual drop system by July 15, 1994. A description of these tests is included in the Test Plan (Appendix A).

3.2 Droplet Generator, SOW 5.2.2

The proprietary droplet generator for the LMJ system will accept the liquefied metal from the fluidizer and provide the instability required to excite the jet stream into a repeatable droplet formation. In addition, the droplets will have a charge induced by an induction plate as they break away from the jet. A signal level will be provided to the charge on the droplets the trajectory through an electric field can be controlled. After being charged, the droplets will continue through an electrostatic deflection field, to impact the target at a precise location.

New verions of the proprietary, continuous mode generation have been designed, fabricated, and tested off line. As mentioned in the last report, problems include stream instability and a lack of consistent droplet formation. Redesigned continuous mode generators continue to be tested.

An initial charging and deflection system has been built and tested for the continuous mode droplet generator. Early problems with electrical fields interference have been identified and are being studied. Other problems include electrostatic buildup and poor response time of the charging ring. A new pulser system has been designed and is being assembled. The first test of the system should be performed in early May.

3.3 Jet/Droplet Stream, SOW 5.2.3

A path for the droplets to be charged and deflected will be provided in the design of the system. The path will also provide for alternative atmospheres for experimentation. Controlling the environment was shown in previous research programs to be critical to jetting success. The no lead system jet stream and target chamber if a large plexiglas environment chamber used to provide an insert gast atmosphere. This is a modification of earlier research programs.

The cooper system will require a complete redesign because of its higher temperature. Preliminary design evaluations have concluded the continued need to use an inert environment for copper. The copper manual drop system will provide important design information for this effort.

3.4 Target Chamber, SOW 5.2.4

The test coupons (i.e., samples) on which the experiments will be run, reside in a fixture to hold the coupon and a chamber to provide for controlled inert atmosphere. This chamber will provide controlled heat for coupon preheating and provide for optical observation and instrumentation. In addition to the chamber, a precision motion control system to position the coupon for pattern writing will be designed, acquired and integrated into the LMJ system. A device to catch the unwanted or "guttered" droplets is included in the coupon chamber.

The required level of environmental control for the jet stream for the no lead system has resulted in the target chamber being included in the jet stream's plexiglas environment chamber. A preliminary design of the thermal control for the test coupon and the guttering system has started and will be complete by the design review.

A risk reduction effort has been inititated to study the impact dynamics of the molten droplets impacted by the substrate. This will help to predict droplet impact and solidification parameters including heat transfer. This is important since copper will be difficult to study *"in situ."*

3.5 System Control, SOW 5.2.5

System control addresses all items necessary to control and monitor the process. Subtasks include hardware, software, and integration for process control, environmental control, data

acquisition and safety. The system control will include personal computers, programmable logic controller, data acquisition software. Computer Aided Design (CAD) data, Network Control program interface and custom programming. Facility related subtasks will include, fume handling capabilities, safety systems and thermal management equipment.

The system control computer for the no-lead system has been specified and ordered. A computer from another program has been borrowed for the interim.

The x/y table for the no lead has been designed and fabricated using COMPUMOTOR software running on a personal computer. Industrial Proportional Integral Derivative (PID) controllers are used to control all variable parameters (pressure, temperature). The overall system is monitored using a modified National Instruments software program called LABVIEW which runs on a Macintosh computer. The cooper based system is expected to use the same basic scheme.

Initial results of the no lead system have shown problems such as:

1. Thermal protection

2. Labview software interface

3. Honeywell controller.

These problems are being addressed and modifications are being made to the design.

4.0 SYSTEM TEST AND EVALUATION SOW 5.3

The Test Plan has been developed and is included as Appendix A. Several system and subsystem tests have been concluded including:

- Fluidizer Tests
    - Pressure (June) - completed
    - Temperature (June) - completed
    - Loading (June) - completed
    - Filter Replacement (June) - completed
- Environmental Control Tests
    - Nitrogen Flow (June) - completed
    - Chamber Pressure (June) - completed
    - Chamber Temperature (June) - completed.

All tests were successful. Many important tests are scheduled for July and August including the production of test coupons.

5.0 TEST COUPON EVALUATION, SOW 5.4

The Test Coupon Evaluation task is scheduled to start in July.

6.0 TECHNOLOGY TRANSFER, SOW 5.5

Several United States manufacturers have been contacted for technology transfer. Serious discussions have been held with MPM, General Motors - Delco, and Induim Corporation of America.

APPENDIX A

TEST PLAN

LIQUID METAL JET TECHNOLOGY: AN ALTERNATIVE PRINTED WIRING BOARD PROCESS

For

Texas Instruments, Inc.

June 24, 1994

By

Liquid Metal Jet Research Laboratory
Automation and Robotics Research Laboratory
The University of Texas at Arlington

1.0 INTRODUCTION

This Test Plan is submitted by Texas Instruments Inc. as a deliverable for the research project titled, *Liquefied Metal Jet Technology: An Alternative Printed Wiring Board Process*. This report establishes a test plan for the research prototypes funded by this project. The report is a working document that will be updated as additional information is identified.

2.0 PROGRAM SUMMARY AND SCHEDULE

The objective of this project is to create a demonstrable prototype system capable of manufacturing printed wiring boards (PWBs) via an additive process. The project is based on the liquid metal jet (LMJ) process which is capable of printing very precise droplets of molten metals including solder and copper. This project is a team effort between Texas Instruments Incorporated (TI) and the Automation & Robotics Research Institute of The University of Texas at Arlington (UTA/ARRI)

The primary technical challenge to be met is the development of a print head and system capable of precisely forming and 'printing' extremely small droplets (100 to 1μm) of higher melting point metals such as copper and nonlead-based solder. Unlike current processes, the high precision LMJ technology will be capable of printing a PWB much like an ink jet printer would print a document or label. This printing capability will eliminate many of the ecological problems or by-products associated with the photolithography masking electroplating and chemical etching processes used in PWB manufacturing. In addition to the environmental impact, the LMJ process will favorably impact DoD manufacturing cost, capability and flexibility. With a direct CAD interface, the proposed alternative manufacturing technology will excel in one-of-a-kind rapid prototyping and replication type PWB production. The proposed process can produce PWB patterns with circuit lines smaller than existing technologies. This just-in-time (JIT) fabrication and replication fits directly into such DoD agency missions as the Logistics Command Depot support for the line of battle.

This project represents the first of two steps necessary to develop and implement LMJ technology throughout industry. The demonstration prototype developed in this project will establish the viability of the technology as a significant improvement in PWB affordability, flexibility, and environmental concerns. The next step (i.e., future proposal) will be to convert the prototype into a robust, industrial hardened PWB process which can be used throughout the defense and commercial industrial base.

There are three groups of tests: risk reduction tests, system/subsystem equipment level tests, and process validation tests. These tests are described in the following sections. Where appropriate, design of experiments(DOE) will be incorporated into each test.

The test program schedule with major program milestones is shown in Figure 1.

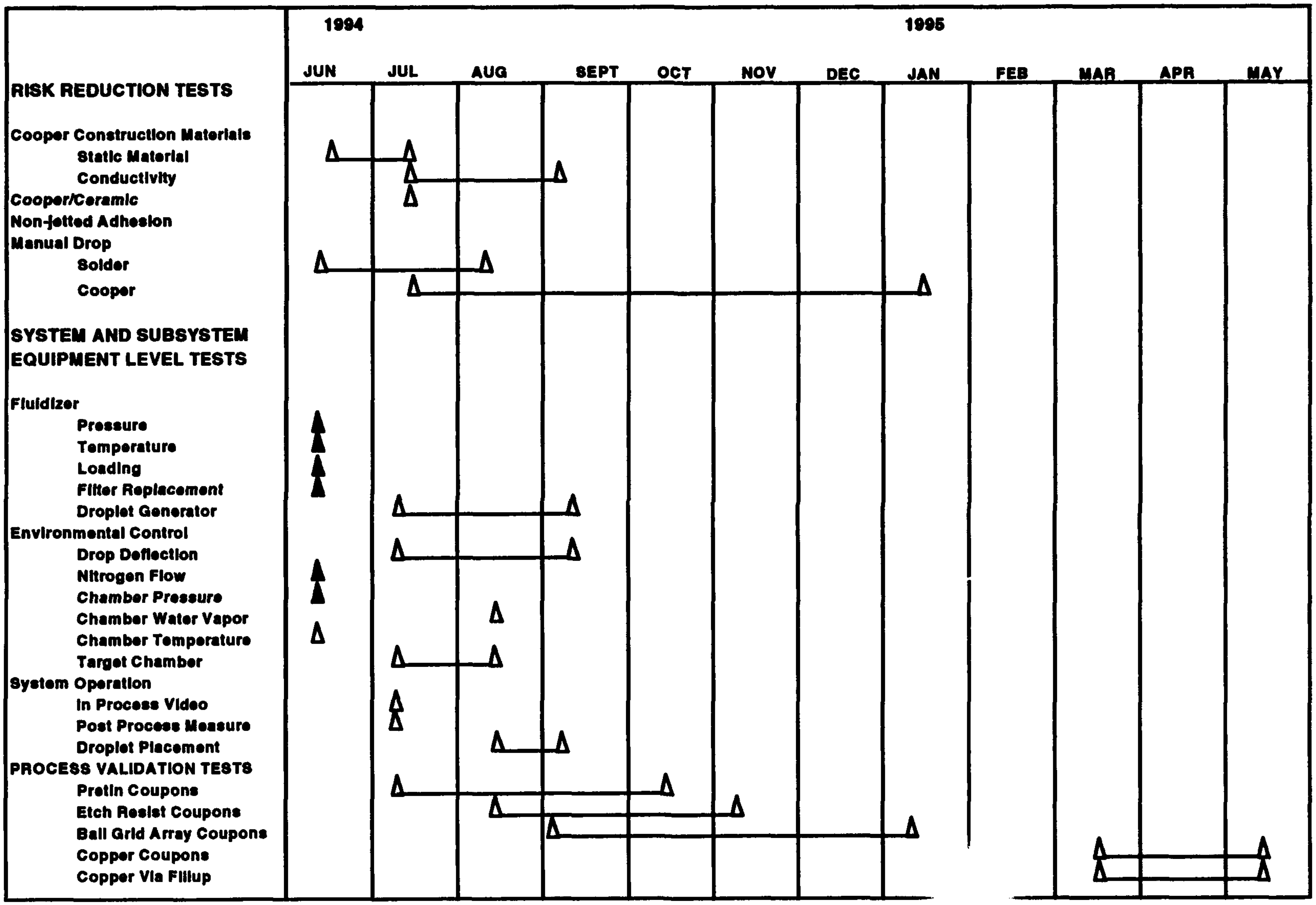

Figure 1. Test Sc..edule

3.0 RISK REDUCTION TESTS

3.1 Copper System Construction Materials (ND)

A series of tests will be performed to evaluate construction materials which will be used in the copper system.

3.1.1 Static Material Compatibility

To test candidate construction materials for suitability as Cu containment from a compatibility stand point, a static heat and soak will be performed (1) in both nitrogen and oxygen environments at a temperature of 2100°F for one hour 8, 16 and 24 hours on a sampling of materials. For each (2) environment, time period, and candidate material, three sample plugs will be prepared as follows. From a 3/4-inch diameter round stock section, a one inch long slugged will be cut with a 1/4-inch diameter hole drilled 3/4-inch deep. A 1/4-inch diameter × 3/4-inch long Cu slug will be inserted into the drilled hole. The samples will then be placed in high temperature muffles and ramped up to temperature 2100°F in both environments. The samples will be soaked for the specified time periods and then allowed to cool by shutting down the muffle. The samples will then be analyzed at UNT and UTA - ARRI for reactivity w/Cu and possible oxidation as well as changes in hardness, strength, composition, and other mechanical/physical properties.

3.1.2 Conductivity/Resistivity/Power Requirements (Static Tests)

To test candidate construction materials for use as electrical leads, wiring, etc. at temperatures of 2100°F, the candidate materials will be placed in a high-temperature muffle, brought to temperature, and held there while a known current is applied over a known length of wire at a known voltage. From the data obtained, the necessary power requirements and conductivity/resistibly changes will be calculated.

3.2 Non-Jetted Copper Adhesion to Substrates and Filters

A series of simple tests will be performed to evaluate the adhesion of non-jetted copper which has been melted on various high temperature substrates (ALN, Beo, etc.) under various conditions of surface roughness and chemical activation. Small copper flakes will be manually placed on the substrate and heated to 2200°F in an inert environment for a short period of time (one hour). After cool down, the substrates will be evaluated for adhesion, metal/substrate intermetallics, and oxide inclusion. Tests will be performed by UTA with evaluations performed by The University of North Texas.

3.3 Manual Drop System for Copper

The manual drop system is being developed to investigate several technologies and design decisions prior to fabricating the copper system. Areas to evaluate for copper include evaluate

melting methods chosen, heat transfer, impact dynamics, copper/substrate interface, environment requirements, thermal management and satellite formation. This test is not a formal test but rather a series of tests samples to evaluate design alternatives and Cu/substrate interface.

4.0 SYSTEM AND SUBSYSTEM EQUIPMENT LEVEL TESTS

The system and subsystem levels tests will be used to verify that equipment performance requirements have been met. For this research program, the tests will consist of a series of simple demonstrations. These demonstrations will consist of testing the equipment to the requirements listed in Sections 4.1 through 4.5. After completion of all tests for a particular subsystem, a test report will be submitted.

4.1 Fluidizer Tests

- Pressure: 500psi, maximum:

  Bring fluidizer temp to 750°F. take pressure up to 500 psi in increments of 100 per 10 minutes. Hold at 500 psi for one hour and check for leaks.

- Temperature:

maximum temperature:	tin 750°F
	copper 2,300°F
operating temperature:	tin 550°F
	copper 2,150°F

  temperature control tolerance: ± 5%

  Set temperature set point at 500°F and allow to settle (about 1 hour). Then bring set point to 750°F and allow system to settle. Check that temperature is within ± 37°F.

- Time to load, melt and prepare metals

tin:	2 hours
copper:	4 hours

  Start Timer load pot with metal close and send pot. Set temperature at desired melt point. Stop timer when temperature is achieved.

- Filter Replacement

  less than 1 hour (after cooling); may not be used in copper system

  start timer, change filter, heat up system, and stop timer

4.2 Droplet Generator Tests

- Process Speed: 5,000 - 30,000 drops/second
- Bring system to appropriate temperature and pressure to establish jet. Activate head and scan frequency to establish breakup. Reduce frequency and pressure to lowest opening limit. Record lower breakoff limit. Raise pressure and frequency to highest operating record upper breakup limit. Compare results to operating specifications.
- Nozzle Replacement less than 1 hour (after cooling)

  After system has cooled, start timer, replace nozzle, stop timer when finished

4.3 Environmental Control Tests

- Drop Deflection and Charging: Deflection distance: > 0.1-inch: Enable 100% deflection to ensure that all balls are deflected > 0.1-inch and then collect individual uncharged balls.

  Hookup a water manometer to chamber initiate gas flow and allow to stabilize, read manometer and check to see that pressure is less than 2-inches water column.

- Nitrogen/Argon Flow, use calibrated flow meter to check flow

  0-100 Scfh @ 1-inch WC

  Positive Pressure: less than 2-inch WC

- Water Vapor: < 10 ppm

  Hook up a water vapor analyzer to chamber initiate gas flow and allow to stabilize. Allow system to purge and watch for water vapor percent to go to or below 10 ppm.
  (takes about 2 hours)

- Temperature: Between ambient and 100°F

  Pressure system place an electric heater and thermometer in chamber and activate heater. Allow temperature to rise to 100°F and turn heater off. Observe seals and read O_2 Sensor for O_2 leaking into system.

4.4 Target Chamber Tests

- Vary coupon temperature, ambient to 300°F ± 5% (copper may vary)

  Place a coupon in coupon holder. Place a thermometer on the coupon. Initiate coupon leader - set controller to 300°F. Observe temperature rise and let system settle. Record final temperature.

4.5 System Operation and Control Tests

- In process video observation capability

  Jet verification (breakup) field of view, .02-inch - .06-inch range

  Establish a LMJ. Use video camera to observe jet. Verify focus and illumination. Measure capability of video observation system. Focal length.

- Post Process Measurements made from Videotape of In-Flight Droplets

  Calibrate video system. Determine resolution of video system based cm. Pixel and image size. Observe video and measure parameters.

- Prototype Droplet Placement Precision

Initial placement accuracy for table:	± .002 inch
Repeatability Error Budget:	± .010 target/goal
	error budget
Note: (Equipment for measuring	± .002 jet stability
droplet placement at this level of	± .002 air flow
precision is not currently available)	± .002 material effects
	± .002 table vibration
	± .001 coupon movement
	± .001 X/Y table

Table: set up 2-inch travel dial indicators on X axis and Y axis of both ends table (4 total)

Zero indicators. Send table information (indicators 1 inch X and 1 mph Y. Read and record indicators on side 1. Return to original position. Read and record indicators on side 2. Repeat test 10 times. Analyze results for accuracy and hysterics and repeatability.

5.0 PROCESS VALIDATION TESTS

Process validation will consist of evaluating test coupons which have been manufactured using the LMJ system. Two test coupon patterns for this research program have been selected. The first pattern will be used for process validation and is shown in Figure 2. The process validation coupon includes lines, ball grid arrays, vias and symbols/characters. The size of these features will vary depending on the size of the metal spheres being jetted (see Table 1). The second test coupon shown in Figure 3 will be used to investigate the capability of LMJ to meet future production requirements. This coupon represents the state of the art for each application. The state of the art pattern includes different sizes of straight lines, six channel routing, vias, plated through holes, ball grid arrays, and symbols/characters. For this contract, the process validation coupon is a program requirement, whereas, the state of the art coupon will be used as a program goal if time permits.

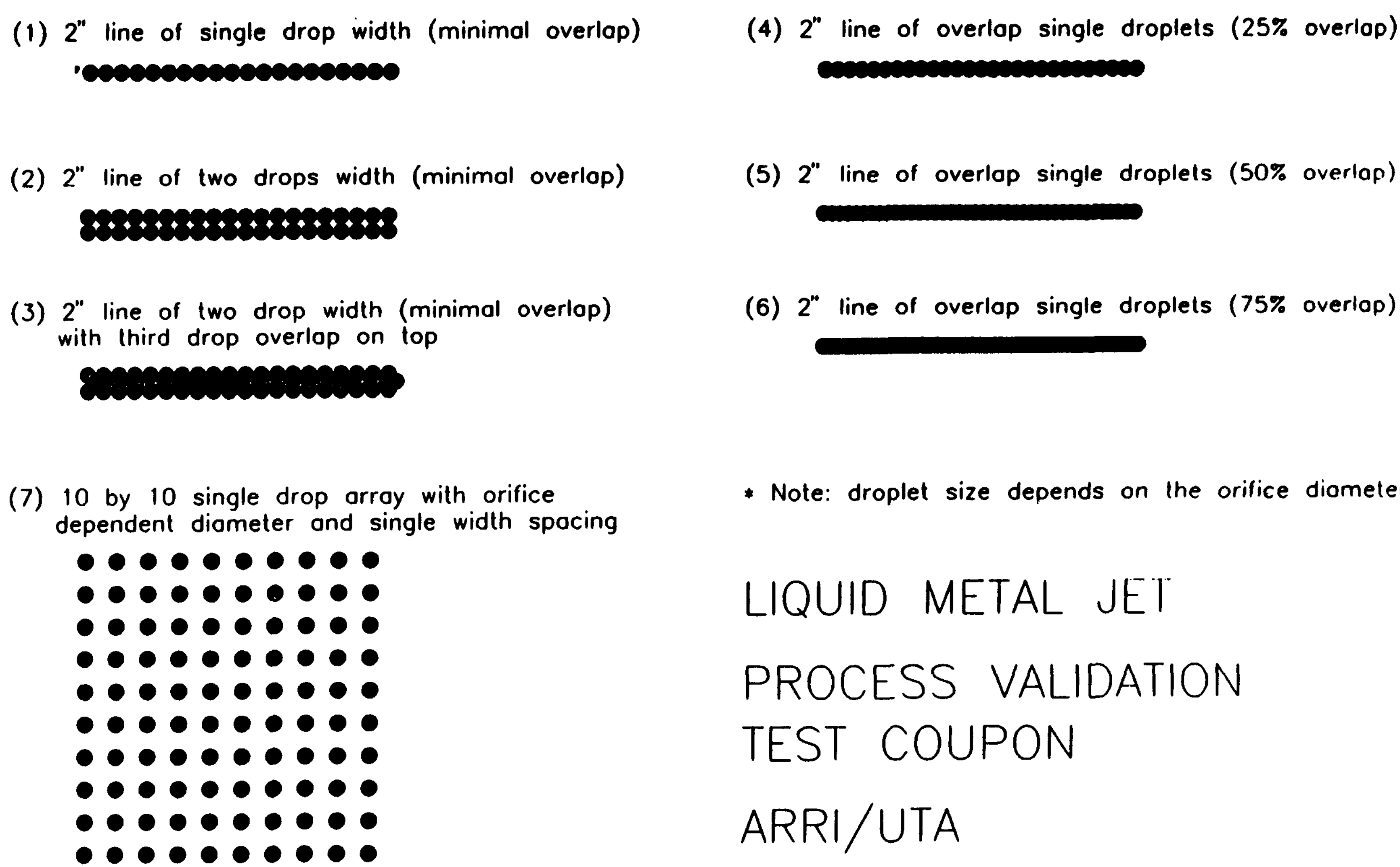

Figure 2. Process Validation Test Coupon Pattern

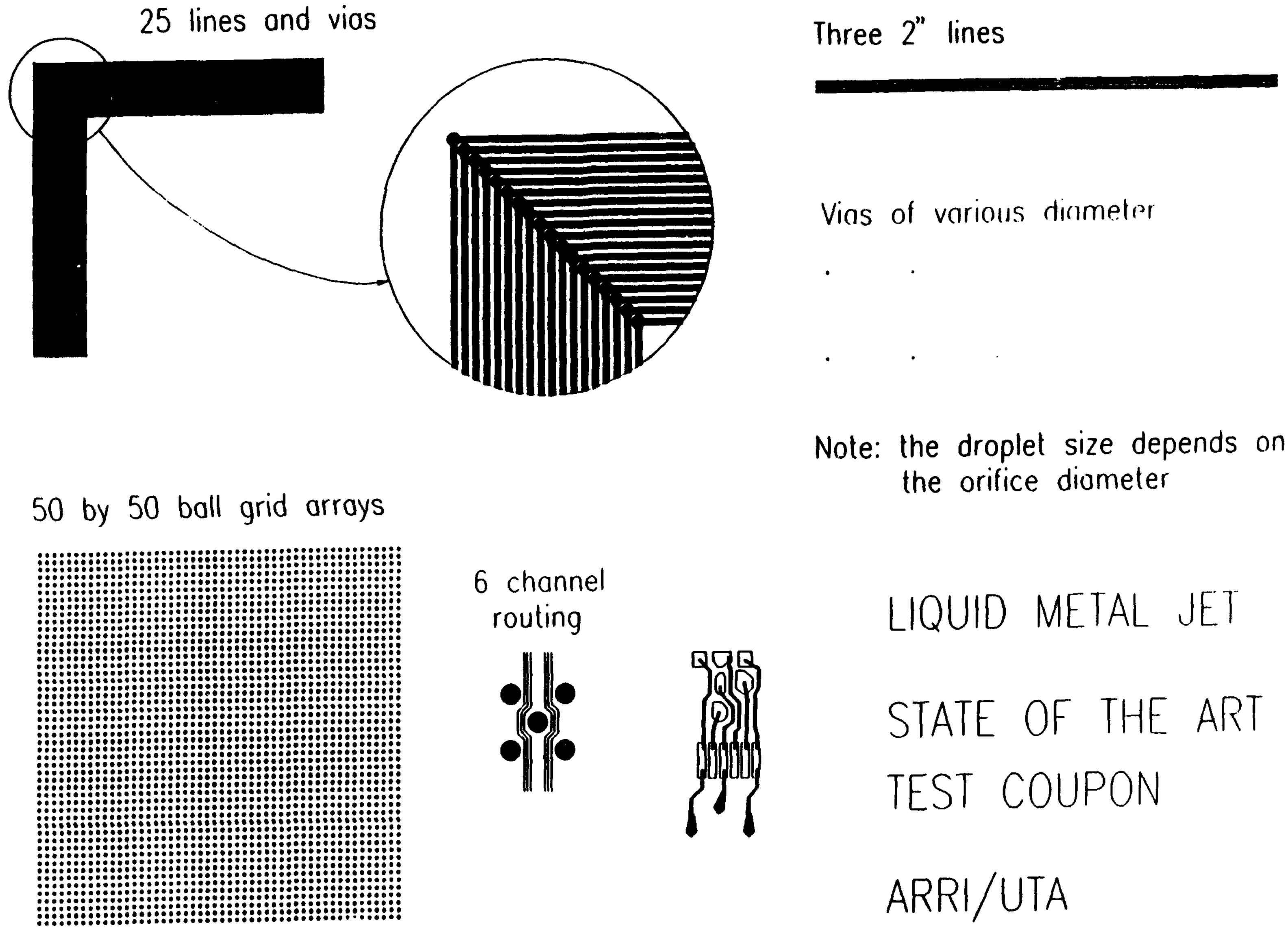

Figure 3. State-of-the-Art Test Coupon Pattern

5.1 Process Requirements

- Line Width(s). Some of the major process requirements and test variables are listed below.

Table 1: Test Targets

Approximate	Droplet diameter	Orifice size
.010 inch (Common Practice)	185μ	100μm
.005 inch (Current State of the Art)	90μ	50μm
.002 inch (Future Breakthrough)	45μ	25μ

- Pad Size: 0.010, 0.005, 0.002-inch.
- Actual line and pad height: determined by droplet size and impact dynamics
- Copper via fill up (via sizes): 3 mil deep, 6 mil × 60 mil, 5 × 3? (TBD)
- Controlled Test Variables
  - Metal Temperature
  - Ambient Air Temperature; ambient to 100°F (copper TBD)
  - $O_2 < 500$ ppm
  - $H_2O < 10$ ppm
  - Substrate Type
  - Substrate Temperature; ambient to 100°F (copper TBD)
  - Flux/Chemical Activation
  - Surface Preparation/Roughness

5.2 Process Application Descriptions

Four test applications have been identified to establish the viability of the LMJ process in PWB manufacture. The four applications apply:

- Pure tin to pretin PWB copper circuit paths
- Pure tin as an etch resist to produce circuit paths/pads/vias
- Pure tin solder bumps on PWB substrates for ball grid arrays
- Copper for printed circuit paths and vias.

For the no-lead applications, the test coupons will be 12 × 12-inch (minimum 6 × 6-inches) oxygen free, high conductivity (OFHC) copper clad substrates which can be loaded into a 18 × 12-inch fixture. Since the substrate base is not a critical parameter, FR-4 will probably be used initially. The copper will be degreased and lightly acid etched prior to testing. The coupons will be prepared in a similar procedure used by Sandia National Labs Solder Research Center (see

Section 10.1 of the Requirements Definition Report). Four fluxes will initially be used. These are RMA1, RMA2, OA1, and OA2 which will be mixed 1:1 with alcohol.

For the copper application the test coupons will be 12 × 12-inch (minimum 6 × 6-inches) substrates of different materials which can be loaded into standard 18 × 12-inch fixture. Materials to be evaluated will include FR-4, polyimide, BT, A1O, BeO, A1N, plastic, and any other readily available material. Various materials and methods will be evaluated for pre-cleaning, fluxing, and post processing the various substrates.

To minimize the placement accuracy required for all test application, the pattern will be applied in a non-registered position on the test coupon. This differs from typical PWB applications. Descriptions and requirements for the four test applications are described in the following sections.

Where appropriate, DOE techniques will be used to identify critical variables affecting the process.

5.3 Test Application #1 Pretin - applying pure tin that wets to a copper clad substrate to pretin circuit pads/paths.

The purpose of test application #1 is to simulate the pretin requirements found in PWB manufacturing. Pure tin will be applied in a pattern on the copper clad, non pre-etched, test coupon. Test patterns were selected which represent typical PWB patterns and are shown in Figures 2 and 3. The prototype will be a single shooter (assume one layer of balls).

Requirements and process parameters to be measured from the coupons include:

- **Solderability**

The primary goal of these tests are to determine how well Sn wets the substrate during deposition of the liquid metal. The techniques for assessing solderability on the substrate will include the following tests:

1. Visual Inspection: this may include the use of a stereo microscope to view the samples at up to 10X magnification to detect evidence of non-solderability such as balls not adhering to the substrate, inadequate coverage of the targeted area, voids and measuring the area of spread.
2. Cross-sectional Inspection: pretinned pads or paths will be cross-sectioned and metallurgically polished, and examined by optical and/or Scanning Electron Microscopy to inspect for internal void formation, inclusions, and excessive intermetallic formation. The wetting angle will also be estimated from the cross sectional samples.
3. Peel Testing: Peel tests will be performed following a procedure for peel testing modified from the technical procedures of DuPont Electronics in which pads will be pretinned using the LMJ process and the Sn will be reflowed to solder Cu test wires in place for testing.
4. Thermal Cycling: (TBD)

5. Steam Aging: (TBD):

Dimensional analysis measurements will be made to assess the accuracy and precision of droplet placement to form pads or lines. Measurements will be made using optical and scanning electron microscope where applicable. The measurements to be made include:

- Line width tolerance (mils)
- Line thickness tolerance (mils)
- Surface and edge profile (see Figure 4)
- Indentation/mouse bites (mils)
- Overall slope of top height (degrees)
- Wetting angle (degrees)
- Initial placement accuracy (mils)
- Average overlap accuracy (mils)
- Overlap repeatability (mils)
- Maximum off pattern (mils).

5.4 Test Application #2 Etch Resist - applying pure tin to a copper clad substrate to be used as an etch resist

The purpose of test application # 2 is to simulate the use of tin as an etch resist for producing copper circuit paths by printing circuit paths in tin and then etching away excess copper. Pure tin will be applied on the copper clad test coupon in the same pattern as application # 1 (see Figures 2 and 3). Unlike application # 1, more than one layer of depositions may be required. After the pattern is printed on the test coupon, excess copper on the coupon will be etched away. Tests will then be performed on the copper circuit paths that remain.

Requirements and process parameters to be measured from the test coupons include:

- Etch resistance after etching (to be determined)
- Electrical performance characterization of etched circuit paths (TBD)
- Thermal conductivity (w/m ° k)

Dimension analysis measurements will be made using optical and scanning election microscopes. Measures to be made include:

- Line width tolerance (mils)
- Mask coverage prior to etch
- Line thickness tolerance (mils)
- Surface and edge profile (see Figure 4)

- Indentation/mouse bites (mils)
- Overall slope of top height (degrees)
- Wetting angle (degrees)
- Initial placement accuracy (mils)
- Average overlap accuracy (mils)
- Overlap repeatability (mils).

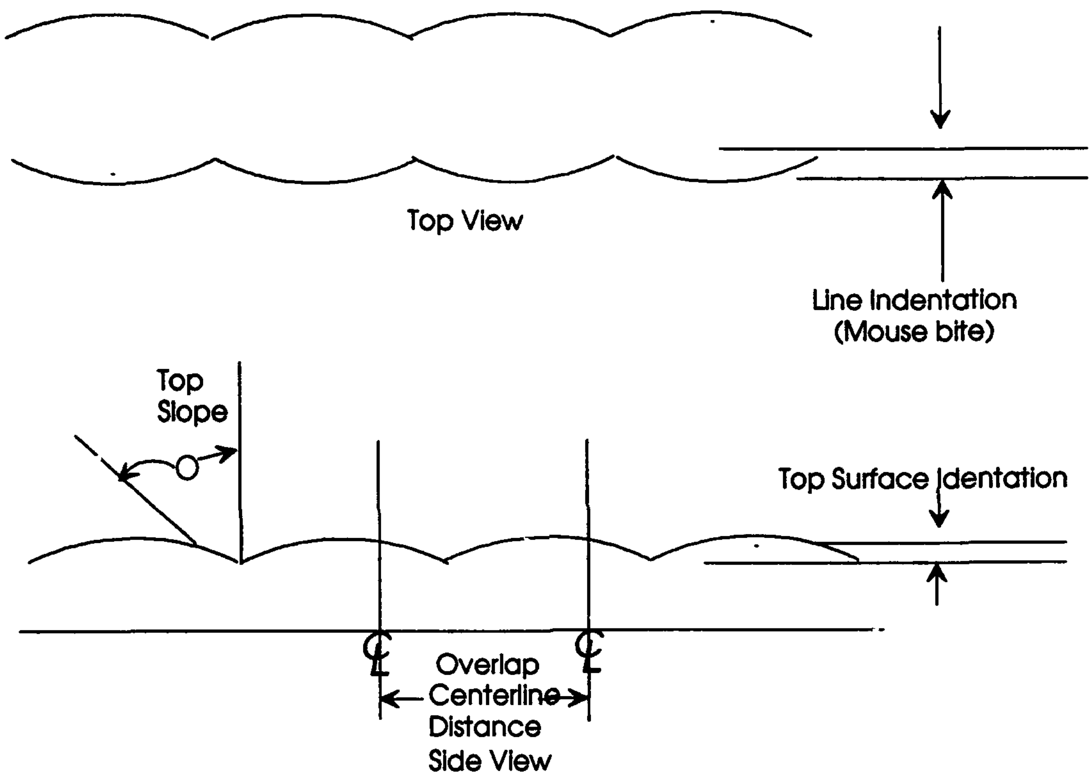

Figure 4. Surface and Edge Profile Description

5.5 Test Application #3: Ball Grid Array description: - applying tin and no lead solder for solder bumping of PWB's for ball grid array applications

The purpose of test application #3 is to simulate the solder bumping process on PWB for ball grid arrays (flip chips). Pure tin will initially be used for the solder bumps. Since no one is using pure tin in this application, no lead solders will also be used if time and resources permit.

Requirements and process parameters to be measured from the test coupons include:

- Oxide inclusion

- Bump test strength (kg/mm^2)- peel off test
- Adhesion
- Pull off test - reliability - fatigue, thermal, vibration.

Dimension analysis measurements will be made using optical microscopes and scanning election microscopes. Measures to be made include:

- Initial placement accuracy (mils)
- Array repeatability
- Average edge distance (mils)
- Minimum/maximum edge (mils)
- Minimum/maximum centerline (mils)
- Average centerline distance (mils)
- Ball thickness tolerance
- Individual splat surface and edge profile tolerance
- Edge diameter (mils)
- Overall slope of top height (degrees)
- Wetting angle (degrees).

5.6 Test Application #4: Copper Circuits description: - applying liquid copper to form circuit paths on various substrates.

The purpose of test application #4 is to simulate the printing of copper circuit paths and filling up vias on various substrates (i.e., additive process). Pure copper will be applied in the same pattern as defined in Figures 2 and 3. Via fill up will be performed on special test coupons which have drilled holes and a backing pad. The tests to be performed for this application will be similar to those for copper and vias paths produced in typical processes. The effects of substrate preparation will be evaluated including chemical activation, oxide removal and surface roughness.

Requirements and process parameters to be measured from the test coupons include:

- Thermal Cycling - TBD
- LMJ copper to resin/substrate; 6 lb/in minimum 0-12 lb/in preferred, on a 1/2 T-Peel (ASTM D-1876) (1972)
- LMJ copper to copper; $\geq$ 10 lb/in, on a 1/2 T-Peel (ASTM D-1876) (1972)
- Surface color (subjective classes), visual
- Conductivity/resistivity (ohm cm)
- Thermal conductivity (w/m °k)
- Electron mitigation (TBD)

- Porosity measure (TBD)
- Elongation of Cu (TBD)
- Metallic/grain structure (size/geometry) - cross section evaluation
- Amount of inclusion (percent of cross section)-electron microscope ≥ 99.98 percent.

Dimensional analysis measurements will be made using optical microscopes and scanning election microscopes. Measures to be made include:

- Line width tolerance (mils)
- Line thickness tolerance (mils)
- Indentation/mouse bites (mils)
- Initial placement accuracy (mils)
- Average overlap accuracy (mils)
- Overlap repeatability (mils)
- Maximum off pattern (mils)
- Surface and edge profile
- Indentation/mouse bites (mils)
- Overall slope of top (degrees)
- Wetting angle (degrees).

[1]E. I. DuPont DeNemours & Co., Inc. "Test Method for Wire Peel Adhesion of Soldered Thick Film Conductors to Ceramic Substrates", The Thick Film Handbook, Section A-74672, Wilmington, DE (March 1971).